# INDUCTION HEATING DEVICES AND METHODS FOR CONTROLLABLY HEATING AN ARTICLE

## Related Application(s)

The present application is a continuation application of and claims priority from U.S. Patent Application Serial No. 10/017,492, filed October 30, 2001, the disclosure of which is hereby incorporated herein by reference in its entirety.

## Statement of Government Support

The present invention was made with Government support under Air Force Research Laboratory Contract No. F33615-00-C-5403 awarded by the United States Air Force. The Government has certain rights in this invention.

## Field of the Invention

The present invention relates to methods and apparatus for controllably heating an article and, more particularly, to methods and apparatus for induction heating.

## Background of the Invention

Silicon carbide (SiC) is increasingly recognized as an effective semiconductor material for electronic devices. SiC possesses a number of properties that make it particularly attractive for applications requiring devices to operate at high temperature, power and/or frequency. SiC exhibits highly efficient heat transfer and is capable of withstanding high electric fields.

It has been demonstrated that hot-wall chemical vapor deposition (CVD) reactors can provide epitaxial layers of SiC with morphology and doping superior to cold-wall systems. See, for example, U.S. Patent No. 5,695.567 to Kordina et

al., the disclosure of which is hereby incorporated herein by reference. In certain processes, such as epitaxial growth processes, management of the thermal profile in the vicinity of the substrate may be of great importance. Temperature gradients may dramatically influence many growth parameters and the qualities of the resulting layers. Where the substrate is disposed on a platter (e.g., for rotation) separate from a surrounding susceptor and induction heating is employed, the platter may be significantly cooler than the internal surfaces of the susceptor. More particularly, the susceptor may be directly heated by an RF field while the platter is only or predominantly heated by thermal conduction and radiation from the susceptor. The substrate may be cooler even than the platter. As a result, a substantial thermal gradient may be manifested between the substrate growth surface and the internal surfaces of the susceptor. The thermal gradient may be further exacerbated by the cooling effect of a process gas flow through the susceptor.

The aforementioned temperature gradient may present a number of problems. Such problems may include the formation of loose deposits (e.g., SiC) on the hot susceptor wall. Such deposits may fall onto the substrate and be incorporated into the epilayers. Moreover, temperature gradients may cause difficulty in controlling material properties as a result of non-controllable variations in the temperature gradient and the narrowing of process windows.

The foregoing problems may also be presented in other types of processes such as other types of deposition processes and annealing processes.

## Summary of the Invention

According to embodiments of the present invention, a heating device for controllably heating an article defines a processing chamber to hold the article and includes a housing and an EMF generator. The housing includes a susceptor portion surrounding at least a portion of the processing chamber, and a conductor portion interposed between the susceptor portion and the processing chamber. The EMF generator is operable to induce eddy currents within the susceptor portion such that substantially no eddy currents are induced in the conductor portion. The conductor portion is operative to conduct heat from the susceptor portion to the processing chamber. The heating device may further include a platter and an

opening defined in the conductor portion, wherein the opening is interposed between the susceptor portion and the platter.

According to embodiments of the present invention, a housing assembly for an induction heating device defines a processing chamber and includes a susceptor surrounding at least a portion of the processing chamber. A thermally conductive liner is interposed between the susceptor and the processing chamber. The liner is separately formed from the susceptor.

The susceptor may include a platter region and the housing assembly may further include: a platter adapted to support the article disposed in the processing chamber and overlying the platter region; and an opening defined in the liner and interposed between the platter region and the platter.

According to method embodiments of the present invention, a method for controllably heating an article includes positioning the article in a processing chamber. An electromagnetic field is applied to a housing about the processing chamber such that eddy currents are induced within an outer, susceptor portion of the housing and such that substantially no eddy currents are induced in an inner, conductor portion of the housing. Heat is conducted from the susceptor portion to the processing chamber through the conductor portion.

Objects of the present invention will be appreciated by those of ordinary skill in the art from a reading of the figures and the detailed description of the preferred embodiments which follow, such description being merely illustrative of the present invention.

## Brief Description of the Drawings

**Figure 1** is an exploded, perspective view of a housing assembly according to embodiments of the present invention;

**Figure 2** is a perspective view of the housing assembly of **Figure 1**;

**Figure 3** is a perspective view of a reactor assembly according to embodiments of the present invention and including the housing assembly of **Figure 1**;

**Figure 4** is an end view of the reactor assembly of **Figure 3**;

**Figure 5** is a top plan view of a bottom susceptor member forming a part of the housing assembly of **Figure 1**:

**Figure 6** is a side elevational view of the bottom susceptor member of **Figure 5**;

**Figure 7** is a cross-sectional view of the bottom susceptor member of **Figure 5** taken along the line **7-7** of **Figure 5**;

**Figure 8** is a cross-sectional view of a top susceptor member forming a part of the housing assembly of **Figure 1** taken along the line **8-8** of **Figure 1**;

**Figure 9** is a cross-sectional view of a side susceptor member forming a part of the housing assembly of **Figure 1** taken along the line **9-9** of **Figure 1**;

**Figure 10** is a bottom plan view of a bottom liner forming a part of the housing assembly of **Figure 1**;

**Figure 11** is a side elevational view of the bottom liner of **Figure 10**;

**Figure 12** is an end view of a rear liner member forming a part of the bottom liner of **Figure 10**;

**Figure 13** is a cross-sectional view of the bottom liner of **Figure 14** taken along the line **13-13** of **Figure 10**;

**Figure 14** is a bottom plan view of a top liner forming a part of the housing assembly of **Figure 1**;

**Figure 15** is a side elevational view of the top liner of **Figure 14**;

**Figure 16** is a cross-sectional view of the top liner of **Figure 14** taken along the line **16-16** of **Figure 14**; and

**Figure 17** is a cross-sectional view of a platter forming a part of the housing assembly of **Figure 1** taken along the line **17-17** of **Figure 1**.

## Detailed Description of the Preferred Embodiments

The present invention now is described more fully hereinafter with reference to the accompanying drawings, in which preferred embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art.

With reference to **Figures 1-4**, a housing assembly **100** and a heating device or reactor assembly **10** including the same according to embodiments of the

present invention are shown therein. For the purposes of description, the housing assembly **100** has a front end **104A** and a rear end **106A** (**Figure 2**). With reference to **Figures 3** and **4**, the reactor assembly **10** further includes insulation covers **16**, **18** surrounding the housing assembly **100**. An electromagnetic field (EMF) generator **11** is provided including an electrically conductive coil **14** surrounding the covers **16**, **18** and a power supply **12** as discussed in greater detail below. The reactor assembly **10** serves as a portion of a hot-wall CVD reactor for processing substrates **5** (**Figure 1**) such as semiconductor wafers using an atmosphere or flow of a processing gas **IG** (**Figure 2**).

Turning to the housing assembly **100** in more detail, the housing assembly **100** includes a bottom susceptor member **110**, a top susceptor member **120** and a pair of side susceptor members **130** joined by pins **139** and arranged to form a box that is open at opposed ends. A bottom conductor member or liner **150** is mounted on the bottom susceptor member **110**. The bottom liner **150** includes a front liner member **154** and a rear liner member **152** which are separable from one another and together define an opening **156** therebetween. The opening **156** overlies and exposes a platter region **112** on the bottom susceptor member **110**. A platter **140** overlies the platter region **112** and is received in the opening **156**. The platter **140** is rotatably centered by a pivot pin **149**. A top conductor or liner **160** overlies the platter **140**. The top liner **160** is supported by flange portions **163** that are interposed between the top susceptor member **120** and the side susceptor members **130** on either side of the housing assembly **100**.

With reference to **Figure 2**, the housing assembly **100** defines a processing chamber or passage **102** extending fully through the housing assembly **100** and communicating with an inlet opening **104** and an outlet opening **106**. More particularly, the passage **102** is defined by the interior surfaces of the bottom liner **150**, the top liner **160**, the side susceptor members **130** and the platter **140**.

Referring to **Figures 5** and **6**, the bottom susceptor member **110** includes holes **110A** to receive the pins **139** or other fasteners. The platter region **112** may be adapted to provide gas driven rotation of the platter **140**, for example, as disclosed in U.S. Patent Application Serial No. 09/756,548, titled *Gas-Driven Rotation Apparatus and Method for Forming Silicon Carbide Layers*, filed January 8, 2001, inventors Paisley et al., the disclosure of which is hereby

incorporated herein in its entirety. An annular, upstanding ridge **114** surrounds the platter region **112**. An upstanding tab **110B** is disposed adjacent the rear end of the bottom susceptor member **110**.

With reference to **Figure 7**, the bottom susceptor member **110** includes a core **115** and a surrounding layer or coating **117**. Preferably, the coating **117** completely surrounds the core **115**. The core **115** is formed of a material that has high purity, is able to withstand high temperatures (e.g., having a melting point greater than 1800 °C), has low chemical reactivity, and has acceptably low electrical resistance. Preferably, the material of the core **115** has an electrical resistivity of no more than about $100 \times 10^{-6}$ ohm-meter. Preferably, the core **115** is formed of graphite (preferably high purity graphite).

The coating **117** is formed of a material that has high purity, is able to withstand high temperatures (e.g., having a melting point greater than 1800 °C, has low chemical reactivity, and has acceptably low electrical resistance). Preferably, the material of the coating **117** has a resistivity that is less than the resistivity of the core **115**. More preferably, the material of the coating **117** has a resistivity that is no more than 20% of the resistivity of the core **115**. Preferably, the material of the coating **117** has a resistivity of no more than about $20 \times 10^{-6}$ ohm-meters. Preferably, the coating **117** is formed of SiC or a refractory metal carbide, more preferably TaC, NbC, and/or TiC. Most preferably, the coating **117** is formed of tantalum carbide (TaC). The coating **117** may be applied to the core **115** by any suitable method. Preferably, the coating **117** is a dense, impervious coating. Preferably, the coating **117** has a thickness of at least about 10 microns.

With reference to **Figures 1** and **8**, the top susceptor member **120** includes holes **120A** to receive the pins **139** or other fasteners. With reference to **Figure 8**, the top susceptor member **120** includes a core **125** and a surrounding layer or coating **127**. Preferably, the coating **127** completely surrounds the core **125**. The core **125** may be formed of the same materials as discussed above with regard to the core **115**, with the same material(s) being preferred. The coating **127** may be formed of the same materials and in the same dimensions as discussed above with regard to the coating **117**, with the same material(s) and dimensions being preferred, and may be applied to the core **125** in the manner described above.

With reference to **Figures 1** and **9**, each side susceptor member **130** includes holes **130A** to receive the pins **139** or other fasteners. With reference to **Figure 9**, the side susceptor member **130** includes a core **135** and a surrounding layer or coating **137**. Preferably, the coating **137** completely surrounds the core **135**. The core **135** may be formed of the same materials as discussed above with regard to the core **115**, with the same material(s) being preferred. The coating **137** is preferably formed of an impervious material. More preferably, the coating **137** is formed of SiC (preferably dense SiC that is impervious and has a 0% porosity). The coating **137** may be applied to the core **135** by any suitable means or methods. Preferably the coating **137** has a thickness of at least 100 microns.

With reference to **Figures 10-13**, the bottom liner **150** is shown therein with the liner members **152** and **154** separated for clarity. The rear liner member **152** includes an end slot **152B** adapted to receive the tab **110B** of the bottom susceptor member **110**. The rear liner member **152** and the front liner member **154** define opposed semicircular recesses **156B** and **156A**, respectively. Additionally, semicircular, downward facing recesses **152C** and **154C** are formed in the liner members **152** and **154** along the recesses **156A** and **156B**.

With reference to **Figure 13**, the rear liner member **152** includes a core **155** and a surrounding layer or coating **157**. Preferably, the coating **157** completely surrounds the core **155**. The core **155** is formed of a material that has high purity, is able to withstand high temperatures (e.g., having a melting point greater than 1800 °C, has low chemical reactivity, and has acceptably low electrical resistance). Preferably, the core **155** is formed of graphite. The core **155** may be formed in the same manner as described above for the core **115**. Preferably, the core **155** has a thickness of at least 0.15 inch. The core is preferably adapted to provide a substantially coplanar upper surface with the platter **140** when in use (i.e., the platter **140** is levitated).

The coating **157** is formed of a material that has low chemical reactivity. Preferably, the coating **157** is formed of SiC or a refractory metal carbide that is compatible with SiC. More preferably, the coating **157** is formed of SiC (preferably dense SiC that is impervious and has a 0% porosity). The coating **157** may be applied to the core **155** by any suitable means or methods. Preferably, the coating **157** has a thickness of at least about 10 microns. The front liner member

**154** is constructed in the same manner as the rear liner member **152**, and has a core (not shown) corresponding to the core **155** and a coating corresponding to the coating **157**.

With reference to **Figures 14-16**, the top liner **160** includes holes **160A** adapted to receive the pins **139** or other fasteners. A wedge portion **162** of the top liner **160** extends with increasing thickness in the direction of the rear end of the top liner **160**. The wedge portion **162** may serve to gradually decrease the boundary layer of processing gas flowing through the passage and the outlet opening **106** to promote transfer of reactants to the substrate surface from the processing gas.

Referring to **Figure 16**, the top liner **160** includes a core **165** and a surrounding layer or coating **167**. Preferably, the coating **167** completely surrounds the core **165**. The core **165** may be formed of the same materials as discussed above with regard to the core **155**. The coating **167** may be formed of the same materials as discussed above with regard to the coating **157** and may be applied to the core **165** in the manner described above. Preferably, the core **155** has a nominal thickness of at least about 0.15 inch.

With reference to **Figure 17**, the platter **140** includes a plurality of recesses on the upper side thereof adapted to hold the wafers **5**. A pin recess **144** for receiving the pin **149** is formed in the lower side of the platter **140**. The platter **140** includes a core **145** and a surrounding layer or coating **147**. Preferably, the coating **147** completely surrounds the core **145**. The core **145** may be formed of the same materials as discussed above with regard to the side wall susceptors **130**. The coating **147** may be formed of the same materials and dimensions as discussed above with regard to the coating **137**, with the same material(s) and dimensions being preferred, and may be applied to the core **145** in the manner described above. Alternatively, the platter **140** may be formed of solid SiC or a solid SiC alloy.

The insulation covers **16**, **18** may be formed of any suitable material to thermally insulate the housing assembly **100**. Preferably, the insulation covers **16**, **18** are formed of a material having high purity, low chemical reactivity and a thermal conductivity of less than about 2 W/m/K in vacuum.

Suitable EMF generators for the EMF generator **11** include a BIG available from Huettinger Electronic of Germany. The coil **14** and the power supply **12** are

electrically coupled such that the power supply **12** may provide an A/C current through the coil **14** at a selected frequency or range of frequencies. Preferably, the power supply **12** is operable to provide a current through the coil **14** at frequencies of between at least 5 kHz and 1 MHz or a subset of frequencies in this range. Preferably, the power supply **12** is operable to provide power in a range of at least 20 kW to 150 kW.

The housing assembly **100** may be assembled as follows. The side susceptor members **130** are mounted on the bottom susceptor member **110**. The rear liner member **152** is placed on the bottom susceptor member **110** such that the tab **110A** is received in the slot **152B** and the ridge **114** is received in the recess **152C**. In this manner, the liner member **152** is positively located and secured in place on the bottom susceptor member **110**. The front liner member **154** is placed on the bottom susceptor member **110** such that the ridge **114** is received in the recess **154C**. Prior to or following placement of either or both of the liner members **152**, **154**, the platter **140** is placed on the pin **149** over the platter region **112** and in the opening **156**. The top liner **160** and the top susceptor member **120** are mounted on the side susceptor members **130**.

In use, one or more of the substrates **5** are placed in the passage **102** on the platter **140**. The power supply **12** is operated to provide a power level and frequency of alternating current through the coil in a known manner to generate an electromagnetic field. The current frequency is selected such that eddy currents are generated in the susceptor members **110**, **120**, **130**. The electrical resistances of the cores **115**, **125**, **135** and the coatings **117**, **127**, **137** convert at least portions of the eddy currents to heat such that heat is generated in the susceptor members **110**, **120**, **130**. However, the current frequency is selected such that substantially no eddy currents are generated in the liners **150**, **160** or the platter **140**. Rather, substantially all of the power from the coil **14** absorbed by the housing assembly **100** is attenuated by the susceptor members **110**, **120**, **130**. Preferably, at least 90% of the power is attenuated by the susceptor members **110**, **120**, **130**, more preferably at least 95%, and most preferably 100%. Accordingly, no or only insubstantial heat is inductively generated in the liners **150**, **160** or the platter **140**.

The heat or thermal energy inductively generated in the susceptor members **110**, **120**, **130** is thermally conducted from the susceptor members **110**, **120**, **130**

through the liners **150**, **160** and the platter **140** to the passage **102**. The substrate **5** is thereby heated by conduction (through the platter **140**), radiation and convection. Preferably, the substrate **5** is heated to a temperature of between about 1400 and 1800 °C. Notably, and preferably, the platter **140** directly overlies the platter region **112** of the bottom susceptor member **110** without a portion of the liner **150** being interposed therebetween. The coatings **157**, **167** on the liners **150**, **160** may provide thermal breaks from the susceptor members **110**, **120** to further promote thermal uniformity.

In this manner, the internal surfaces of the housing assembly **100** (i.e., the surfaces in fluid communication with the passage **102**) are maintained at a more spatially uniform temperature so that the thermal gradients in the vicinity of the substrate are reduced. Restated, a more isothermal environment may be created in the passage **102** for the substrate **5** such that the temperature of the portion of the housing assembly **100** in contact with the substrate **5** (i.e., the platter **140**) is at substantially the same temperature as the other surfaces defining the passage **102** (i.e., the interior surfaces of the liners **150**, **160** and the side susceptor members **130**). The substrate **5** may therefore itself be substantially the same temperature as the surfaces defining the passage **102**. As a result, the aforementioned problems associated with undesirably large thermal gradients may be reduced. For example, the formation of loose deposits may be eliminated or reduced. The process (e.g., an epitaxy process) may be more accurately controlled.

During the reacting process, the processing gas **IG** (**Figure 2**) may be flowed into the passage **102** through the opening **104**. The processing gas **IG** may include precursor gases such as silane ($SiH_4$) and propane ($C_3H_8$) introduced with and transported by a carrier of purified hydrogen gas ($H_2$). The processing gas IG passes through the passage **102**. As the processing gas **IG** passes through the hot zone generated by the EMF generator **11**, SiC deposition reactions take place on the substrate **5**. The remainder **OG** of the processing gas exits the passage **102** through the opening **106**. Preferably, the processing gas **IG** is flowed through the passage **102** at a rate of at least 10 slpm.

It may be desirable to remove and replace the platter **140**. For example, it may be necessary to remove the substrate or substrates **5** following processing and replace them with new substrates for processing. Also, it may be desirable to

remove the platter **140** for cleaning or replacement with a new platter. The platter may be conveniently removed by first removing the front liner member **154** and then removing the platter **140**. It may also be desirable to remove either or both of the liner members **152, 154**. Each of these procedures may be executed without disassembling the remainder of the housing assembly **100** or removing the housing assembly **100** from the reactor assembly **10**.

The housing assembly **100** may provide for a more efficient, convenient and durable heating device, particularly where TaC is used for the coatings **117, 127** and SiC is used for the coatings **130, 140, 150, 160**. The TaC coatings **117, 127, 137** may serve to reduce thermal radiation losses and prevent or reduce undesirable sublimation of the SiC coatings. The TaC coating in the platter region **112** of the bottom susceptor **110** may provide a more durable platform for the rotating platter **140**. The provision of the SiC coatings in fluid communication with the passage **102** and in the vicinity of the substrate take advantage of the adherent nature of parasitic SiC deposits to the SiC coatings and the chemical, thermal, mechanical, and structural similarity of the SiC coatings and the SiC substrate **5**. The SiC coatings **137** on the side susceptor members **130** may assist in reducing the heating of the side susceptors due to induction heating.

The provision of liners **150, 160** separately formed from the susceptor members **110, 120, 130** may allow for extension of the service life of the housing assembly **100** as well as reductions in cost of use and downtime. The liners **150, 160** may be cost-effectively replaced when they reach the end of their useful service lives without requiring replacement of the remainder of the housing assembly **100**. Moreover, the liner members **152, 154** can be removed for cleaning (e.g., to scrape away parasitic deposits) without requiring removal of the housing assembly from the reactor assembly **10** or disassembly of the remainder of the housing assembly **100**.

The design (e.g., dimensions, materials, and/or placement) of the liner or liners may be selected, modified or interchanged to shape or control the temperature gradient in the processing chamber. For example, additional liners may be positioned along the side susceptor members **130** or one or more of the liners may vary in thickness or material. The liners may be integrated (e.g., as a unitary sleeve). The liners may be integrally formed with the susceptor member or

members. Preferably, the liner or liners will include an opening corresponding to the opening **156** positioned to receive the platter.

Liners may be selected or interchanged to obtain desired gas flow characteristics. In particular, the top liner **160** may be removed and replaced with a top liner having a differently shaped wedge portion **162** or having no wedge portion.

While certain embodiments have been described above, it will be appreciated that various modifications may be made in accordance with the invention. For example, the processing chamber may be closed at one or both ends rather than providing a through passage **102**. Housing assemblies and heating devices according to the invention may be used for other types of processes and material systems, as well as in other types of deposition systems. In particular, the housing assemblies and heating devices according to the invention may be used for annealing processes. Articles other than semiconductor substrates may be processed.

In other embodiments, end insulation may be placed at either or both ends of the housing assembly **100**. The end insulation, if present, may be shaped like a short cylinder of diameter to match the diameter of the covers **16**, **18**. Passages through the end insulation may be provided to permit the process gas **IG** to flow freely through the processing chamber. The passages in the end insulations may be provided with protection liners, preferably made of silicon carbide coated graphite, that separate the process gas **IG** from the end insulation material which may contaminate the process gas.

While preferred embodiments have been described with reference to "top", "bottom" and the like, other orientations and configurations may be employed in accordance with the invention.

The foregoing is illustrative of the present invention and is not to be construed as limiting thereof. Although a few exemplary embodiments of this invention have been described, those skilled in the art will readily appreciate that many modifications are possible in the exemplary embodiments without materially departing from the novel teachings and advantages of this invention. Accordingly, all such modifications are intended to be included within the scope of this invention. Therefore, it is to be understood that the foregoing is illustrative of the

present invention and is not to be construed as limited to the specific embodiments disclosed, and that modifications to the disclosed embodiments, as well as other embodiments, are intended to be included within the scope of the invention.